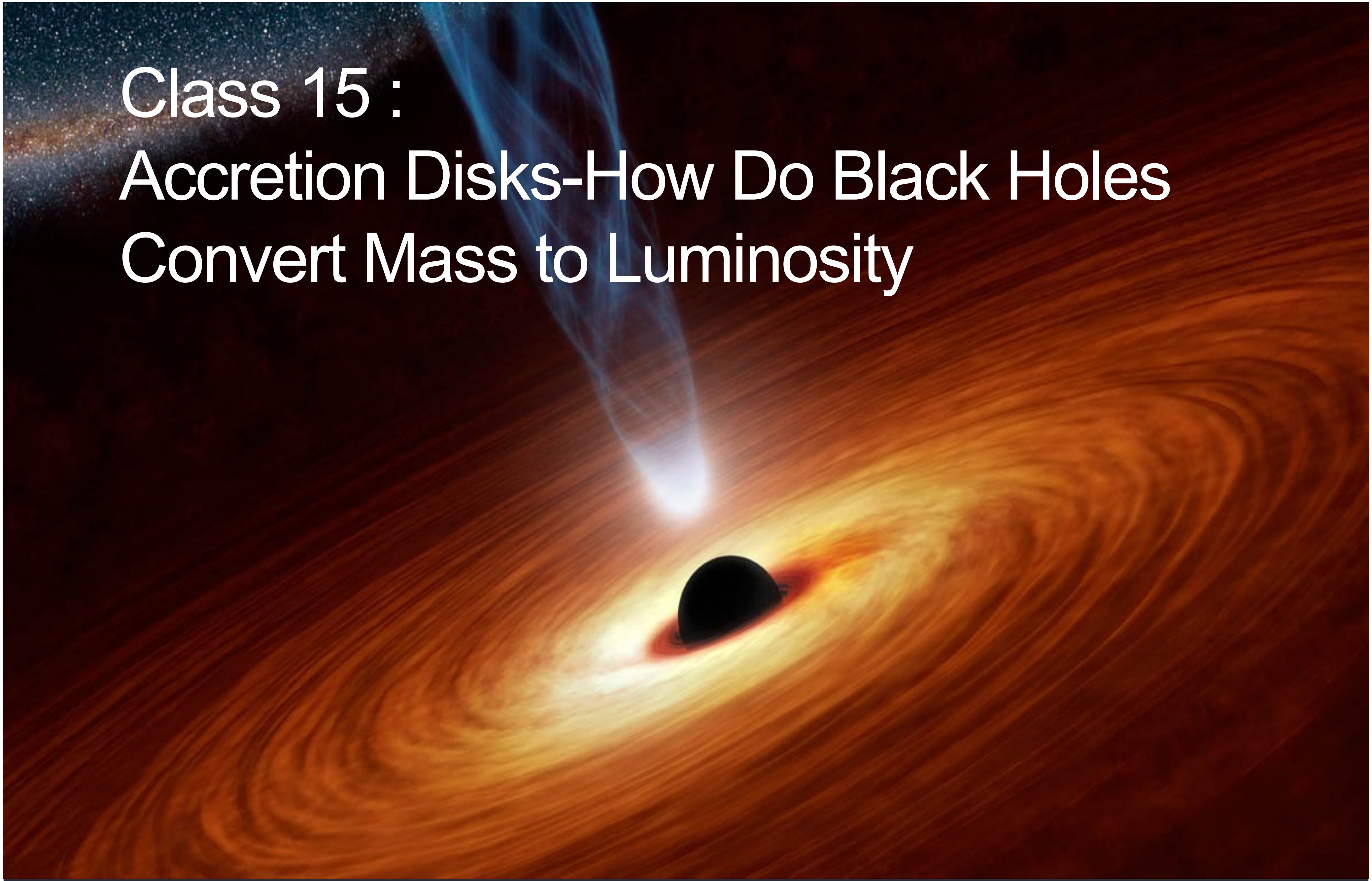

Class 15 :
Accretion Disks-How Do Black Holes Convert Mass to Luminosity

ASTR350 Black Holes (Spring 2022)

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RECAP-

- How quasars were discovered
  - radio astronomy
  - high redshift
  - 'rapid' variability
  - unusual optical spectrum
- How much energy they emit and constraint on size
  - Need lots of energy in a small volume... black holes

This class

- How do black holes shine?
- Accretion Disks!
  - The angular momentum “problem”
  - Viscosity
  - Turbulence and magnetic fields

Accretion

- Matter flowing towards the black hole
- As it gets closer to the BH it gains energy and falls faster and faster
  - If this energy can be converted into 'light' the infalling matter will shine
- The process by which this happens is called accretion
  - However, the matter does not fall directly into the BH (unlike a ball dropped from a height) because of angular momentum

I : Angular momentum

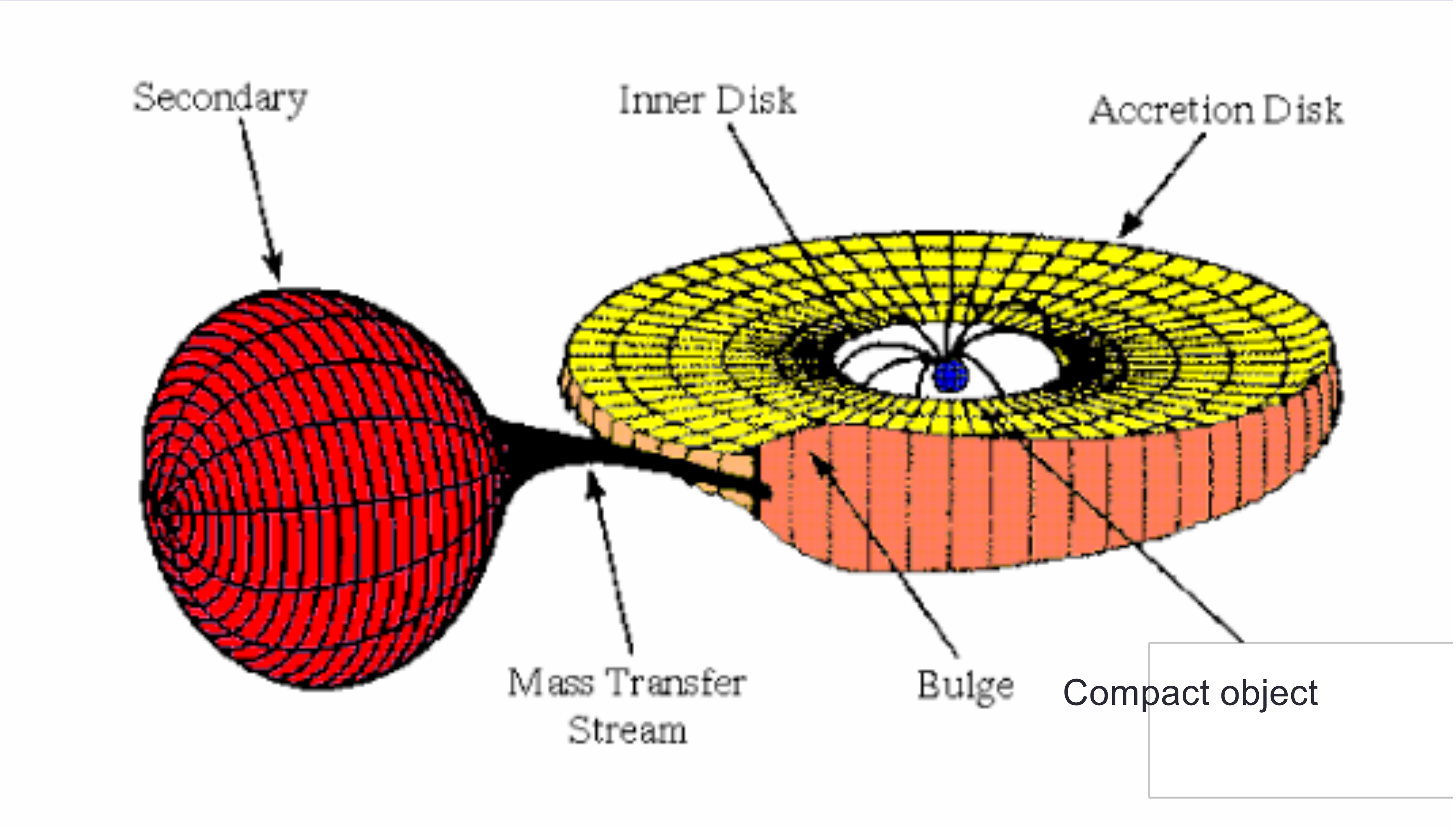
- Recall… momentum is **p**=mv
- The angular momentum about some center of motion is given by **L**=mvr (m=mass, v=velocity, r=distance)
  - Key issue that angular momentum is a conserved quantity if all forces act towards/away from the center of motion.

  - both regular and angular momentum are vectors
  - If we want to be strict, **L**=**r**x**p** where "x" is the cross product

I : Angular momentum

- Consider the X-ray binary scenario…
  - Gas streams flow from companion star towards BH or NS
  - But, star and black hole *orbit common center of mass*, so gas streams do NOT fall directly into the black hole
    - The center of mass of an object is the point at which the object can be balanced.
    - Instead, gas has some angular momentum about the black hole, and goes into orbit around it

Basic Geometry of X-ray Binary



I : Friction

- Need some form of friction (due to viscosity*) that dissipates angular momentum for the matter to move inward and accretion to take place.
- This same 'friction' converts motion into energy
- The inflowing matter forms a disk
  - a differentially rotating system – rotates faster towards center (Keplerian motion)
- This will evolve due to "friction"; 'Nothing happens' in the absence of friction- the energy is liberated via friction.
- It was hypothesized very early that this was not the normal friction (when you rub your hands on a rough surface) but due to the effects of magnetic fields.

Friction-Viscosity

Dictionary definition of viscosity:

- *Viscosity* denotes opposition to flow
  - The state of being thick and sticky in consistency, due to internal friction.
  - "a quantity expressing the magnitude of internal **friction**, as measured by the force per unit area resisting a flow in which parallel layers unit distance apart have unit speed relative to one another.'
- The *viscosity* of a fluid is a measure of its resistance to deformation at a given rate.

I : Angular momentum

- For matter to fall inwards it must lose not only gravitational energy but also lose angular momentum.
- Since the total angular momentum of the disk is conserved, angular momentum needs to be *transported outwards* for matter to accrete.
  - Magnetic field turbulence-enhanced viscosity is the mechanism thought to be responsible for the angular-momentum redistribution.

I : Angular momentum summary

- In directions perpendicular to the accretor's rotation axis, the flow tends to flatten into a disk because the rotation resists the inflow of the material.

- In directions parallel to the rotation axis, the matter contracts toward a plane until the distribution of pressure inside the disk roughly balances the gravitational force.

Accretion -Basic idea

- Viscosity/friction moves angular momentum outward
  - allowing matter to spiral inward
  - further in it falls, the hotter it gets
  - Accreting onto/into the compact object at center (NS has a surface, BH does not)

- gravitational potential energy is converted by *friction* to heat
- Some fraction is radiated as light

Very efficient process: Energy released per mass ~GM/R (the further the material falls towards BH the more energy is available to be converted into heat/light)

Can be ~$0.1c^2$ at ISCO, or ~10^{16} J/kg

Nuclear burning releases 'only' ~7×10^{14}J/kg (needs a surface to 'burn' on) (0.007 of mc^2)

How Much Energy Gets Released

So, the total luminosity liberated by accreting a flow of matter is

$$L = \left[0 - \left(-\frac{GM}{2r_{\rm in}}\right)\right]\dot{M} = \frac{GM\dot{M}}{2r_{\rm in}}$$

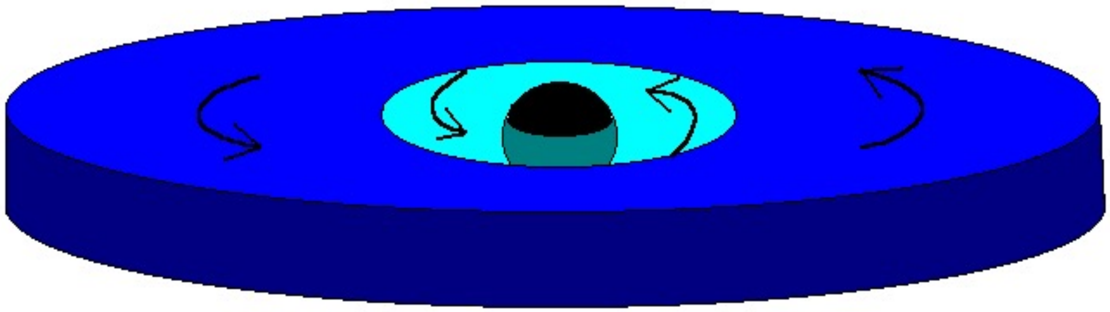
Emitted luminosity

Initial energy (at infinity)

Final energy

Mass flow rate

- **Total luminosity of disk depends on inner radius of dissipative part of accretion disk r_{in}**



- For a disk that extends down to the innermost stable orbit ISCO for a <u>non-rotating black hole,</u> simple *Newtonian* calculation gives…

$$L = \frac{GM\dot{M}}{2(6GM/c^2)} = \frac{1}{12}\dot{M}c^2$$

- More detailed relativistic calculation gives…

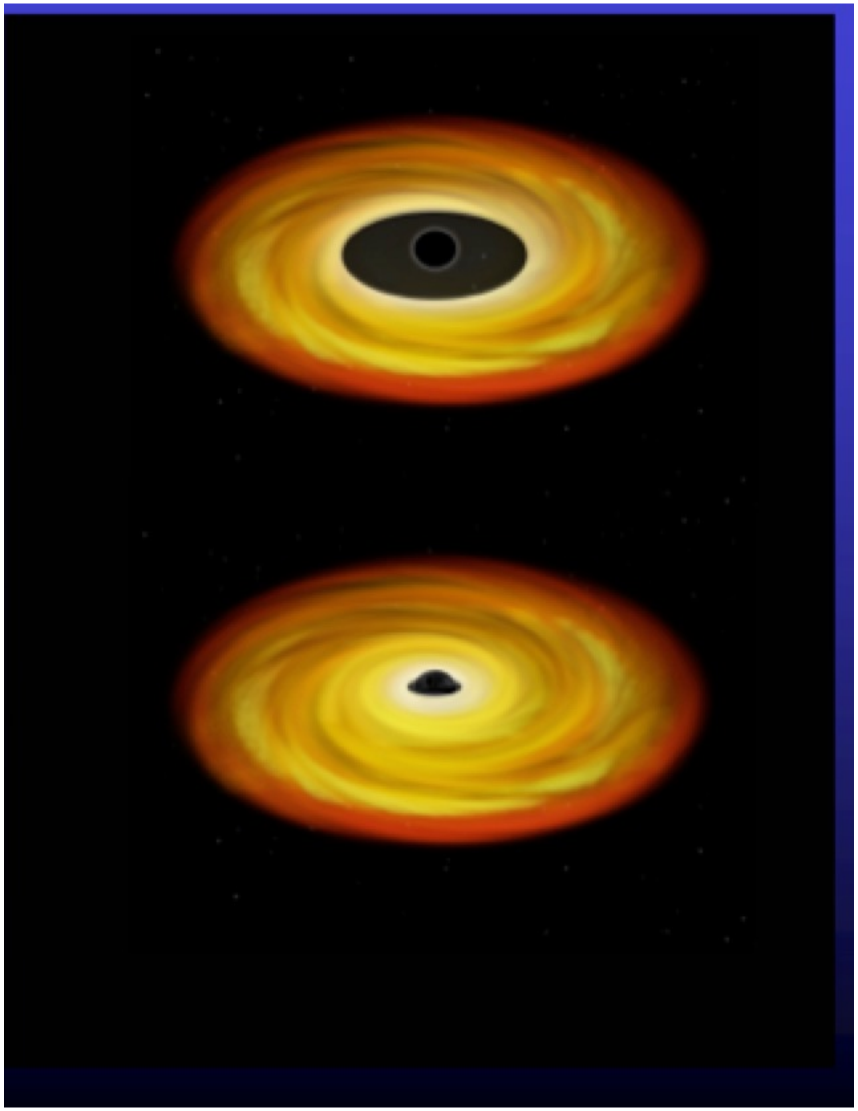
$$L = \left(1 - \sqrt{\frac{8}{9}}\right)\dot{M}c^2 \approx 0.06\dot{M}c^2$$

Relativity matters

Difference Between Schwarzschild and Kerr Black Holes

Remember that a spinning (Kerr) black hole has smaller R_{ISCO} than a Schwarzschild one (assuming that the gas orbits in the same direction that the hole spins)

- thus R_{inner} is smaller and more energy gets released in the accretion disk for a spinning BH- especially in the inner, hottest parts



Angular Momentum-Again

- Consider a parcel of gas with mass m in orbit about a black hole with mass M. Recall that the orbital velocity is

$$V = \sqrt{\frac{GM}{r}}$$

  - Angular momentum about the black hole is

$$L = mvr = m\sqrt{\frac{GM}{r}}r = m\sqrt{GMr}$$

  - So, to get closer to the black hole, the piece of gas must lose its angular momentum… but what about conservation of angular momentum?

Thin accretion disks

Accretion disks form due to angular momentum of incoming gas

Once in circular orbit, specific angular momentum (i.e., per unit mass) is

$$J = vr = \sqrt{GMr}$$

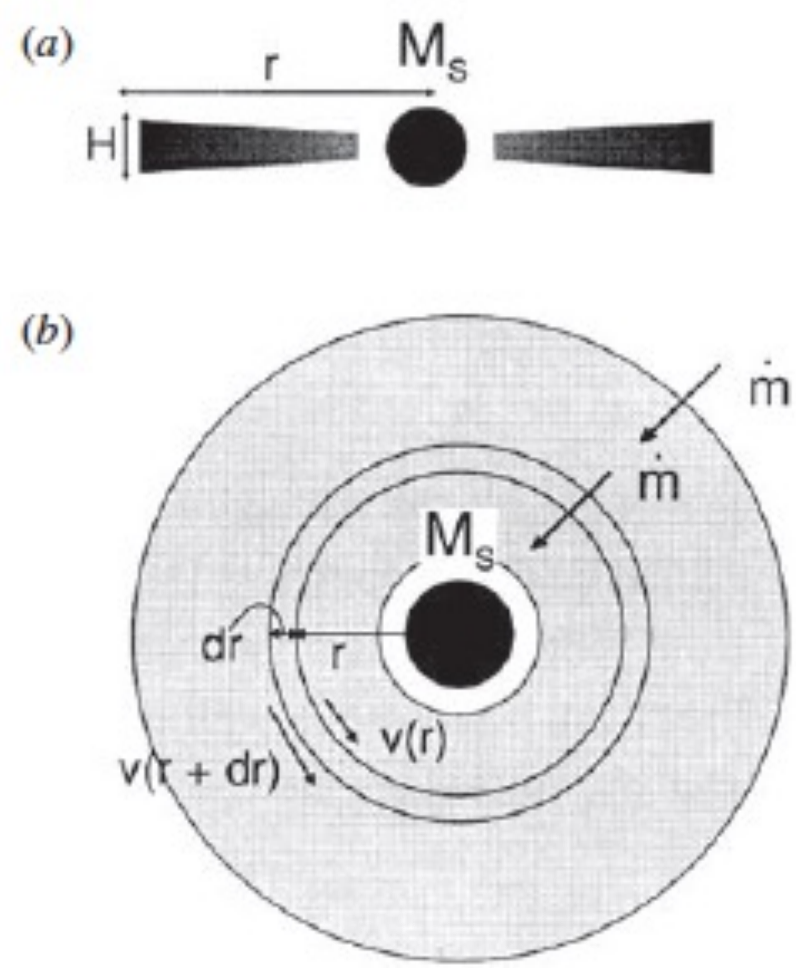
So, gas must shed its angular momentum for it to actually accrete…

Releases gravitational potential energy in the process!

Matter goes in, angular momentum goes out!

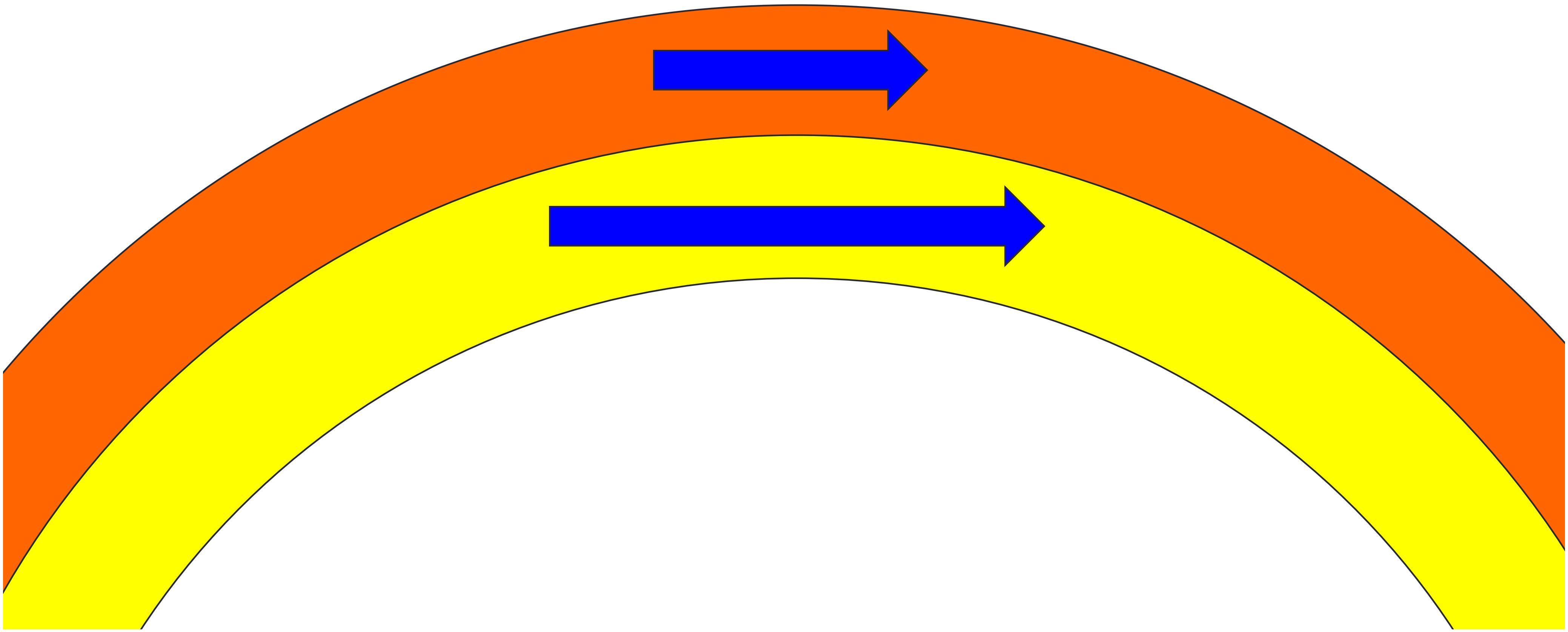
Angular velocity $\Omega \sim R^{-3/2}$

gas rotates faster towards center



II : Sheared flow

- The accretion disk is a "sheared flow"
  - Orbital velocity increases as you move inwards
  - Rings of orbiting gas can "rub" against each other



- Viscosity is the ability of a gas/fluid to exchange momentum with neighboring gas/fluid if there is a shear flow
- So, if gas has viscosity then…
  - Inner/fast ring is being slowed down by outer/slow ring… and vice-versa
  - Angular momentum is being moved outwards through the disk
  - This lets material flow inwards!

- Viscosity in the differentially rotating gas in the disk causes a flow of angular momentum outwards and the balance between centrifugal force and gravity then leads to an inward flow of matter.
- Energy is liberated by the viscosity
- limits to growth rate set by Eddington limit (from last lecture)

- Given the typical densities and temperatures in accretion disks, "standard" viscosity is too low to drive the inward drift.
- It is thought that the friction comes from turbulence due to the rotation of the disk, amplifying any magnetic fields that are already there. This turbulence provides the effective viscosity that drives the drift of matter inward while transporting angular momentum outward.
- The emission from the disk contains information about the rate at which mass flows through the disk and about the temperature distribution on the surface of the disk.

The Process

- Matter enters the accretion disc and it flows down in an inward spiral.

Viscosity causes frictional heating which radiates energy away, reducing the particles' angular momentum

- The loss of angular momentum reduces the velocity
  - at a slower velocity, the particle falls to a lower orbit, and a portion of its gravitational potential energy is converted to increased velocity and the particle gains speed.
    - Thus, the particle has lost energy even though it is now travelling faster than before

A crude model of a disk around a BH

- Remember that the Eddington limit of luminosity is proportional to the mass M of a BH: L~M
- Remember that the inner edge of the disk has a radius also proportional to M: R~M
- Thus the area near the inner edge of the disk is proportional to $A \sim R^2 \sim M^2$.
- For a blackbody, recall that $L \sim AT^4$, where T is the temperature
- Thus at Eddington (or fixed fraction) $M \sim M^2T^4$, or $T \sim M^{-1/4}$
  Inner disk temperature drops with increasing M
  Can use this to crudely estimate BH mass!

III : Turbulence

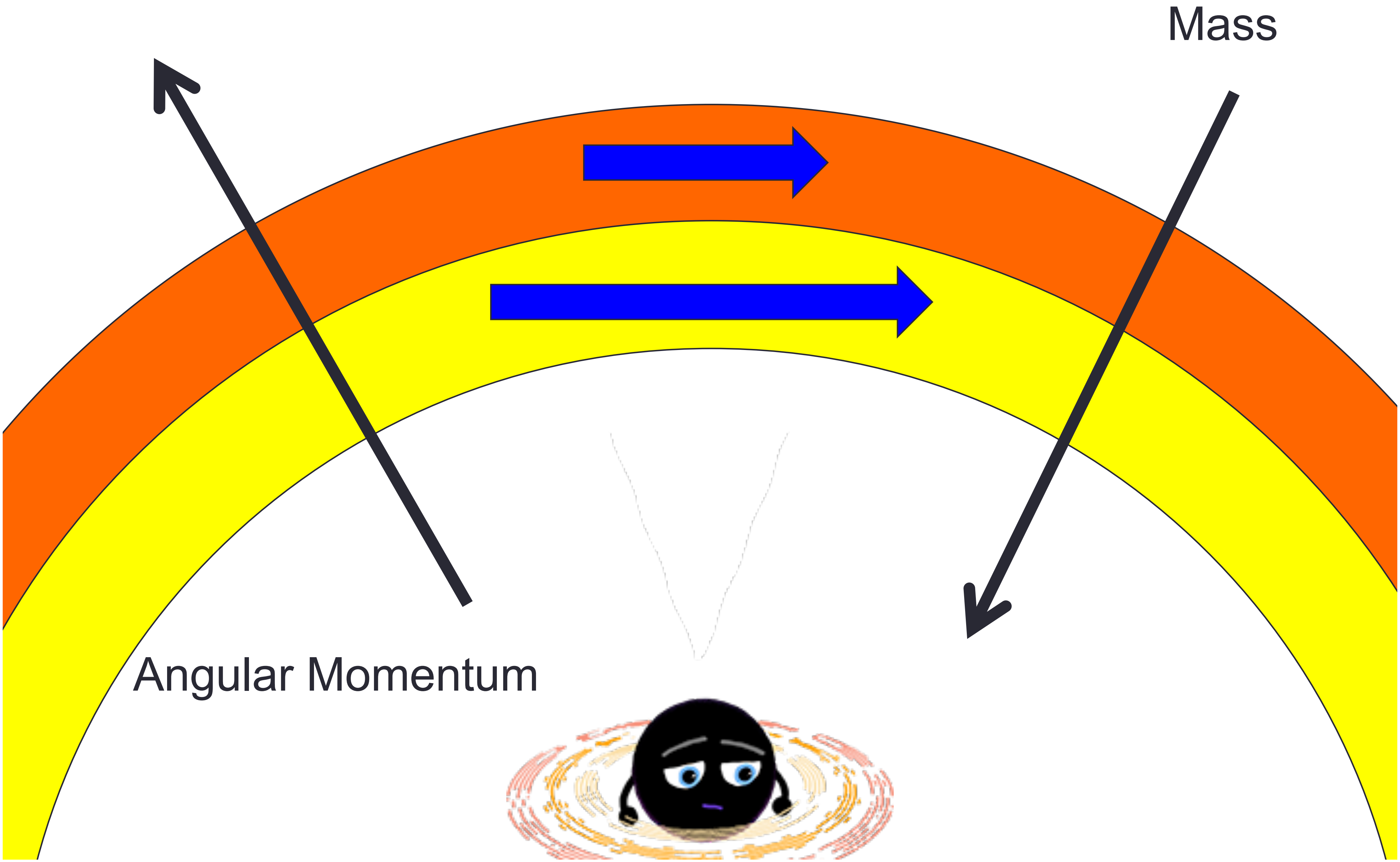
- Modern ideas suggest that the flows in accretion disks are not smooth, they are turbulent.
  - Motions of an individual parcel of gas chaotic
  - The turbulence induces an "effective viscosity"
  - This allows the angular momentum to be moved and the gas to actually fall inwards (accrete)

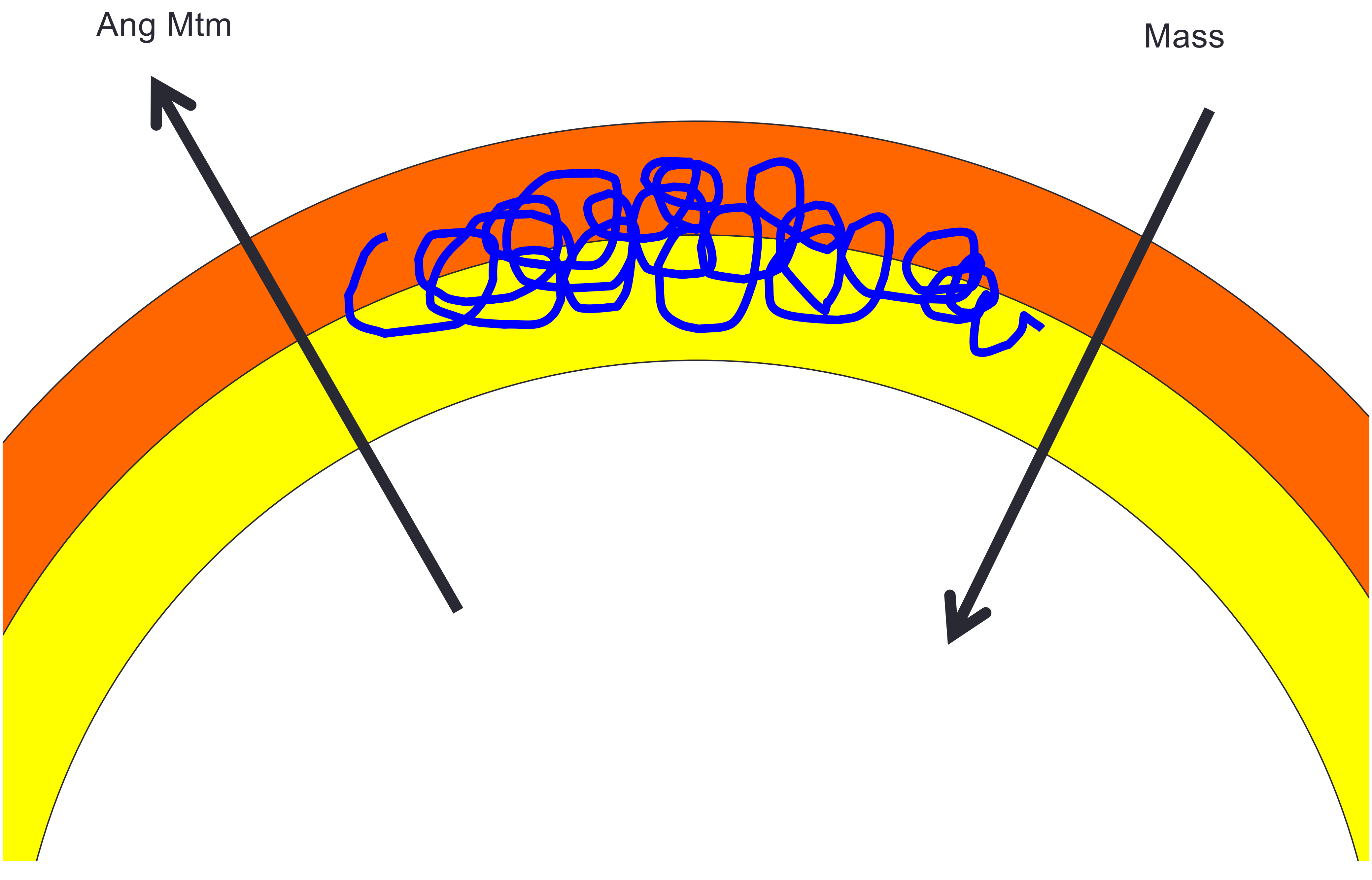
- But WHY is the gas turbulent?
  - Maybe it just happens naturally with such fast flows?
  - But, today it is thought that magnetic fields are very important

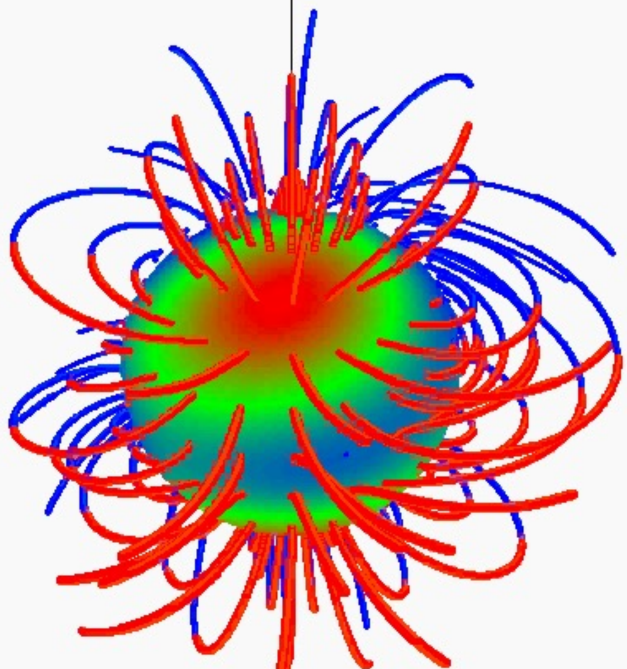
The magnetorotational instability-Physical Model of Viscosity

- Major breakthrough in 1991… Steve Balbus and John Hawley (re)-discovered a powerful magneto-hydrodynamic (MHD) instability
  - Called magnetorotational instability (MRI)
  - MRI effective at driving turbulence
  - Turbulence transports angular momentum in just the right way needed for accretion

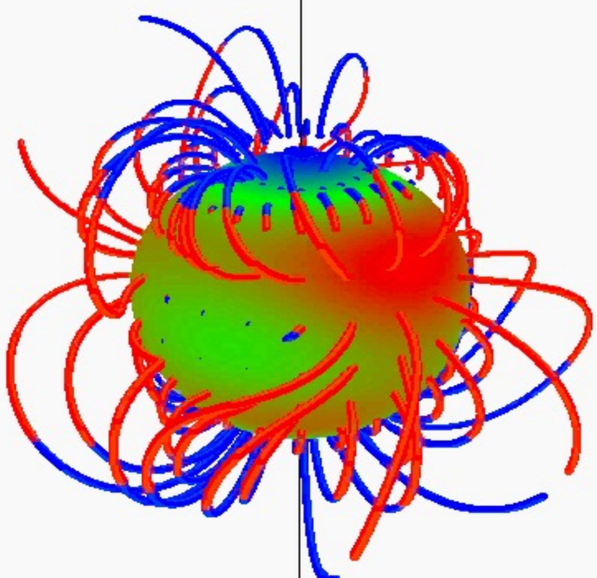
- Two satellites connected by a weak spring provide an excellent analogy for understanding the MRI.


Mass
Angular Momentum


Ang Mtm
Mass



Slide courtesy of D.Lathrop (UMd)



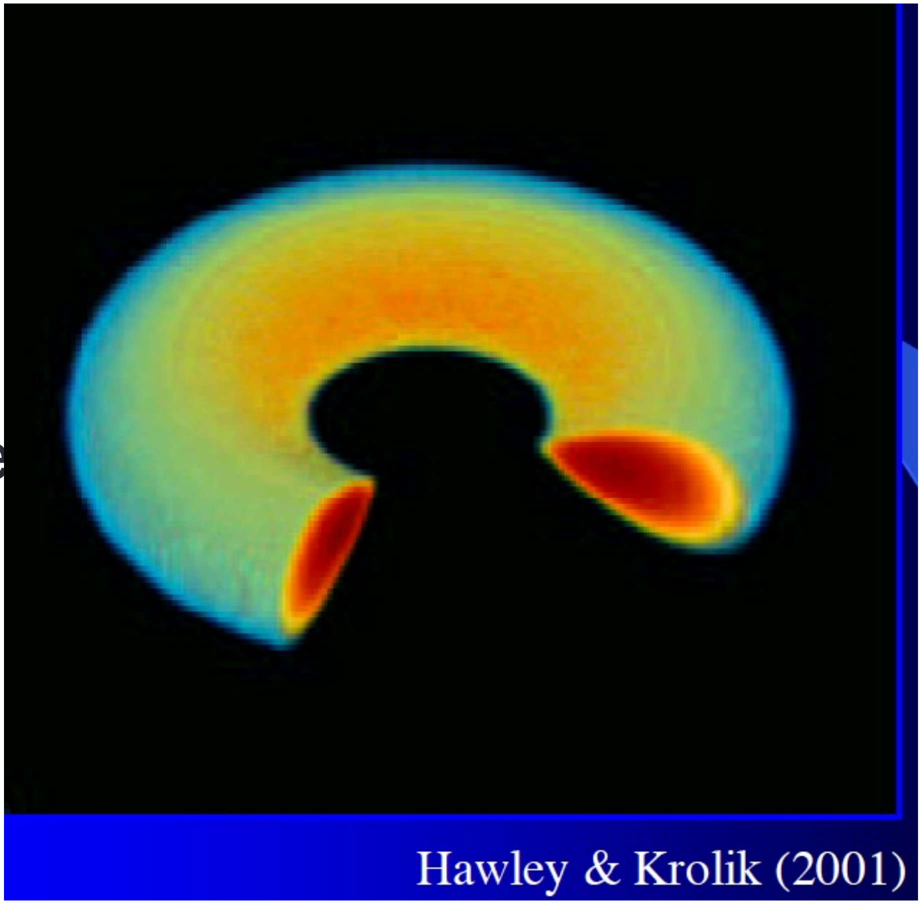
the wide range of time and length scales in turbulent flows at realistic astrophysical parameters is very difficult to calculate in direct numerical simulations.

Laboratory

experiments can provide a great deal of data in parameter space beyond that reached in practical theoretical studies

Theoretical Calculation of Accretion Disks

These use the world's largest computers to calculate how the the Magneto--Rotational Instability (MRI) 'works"



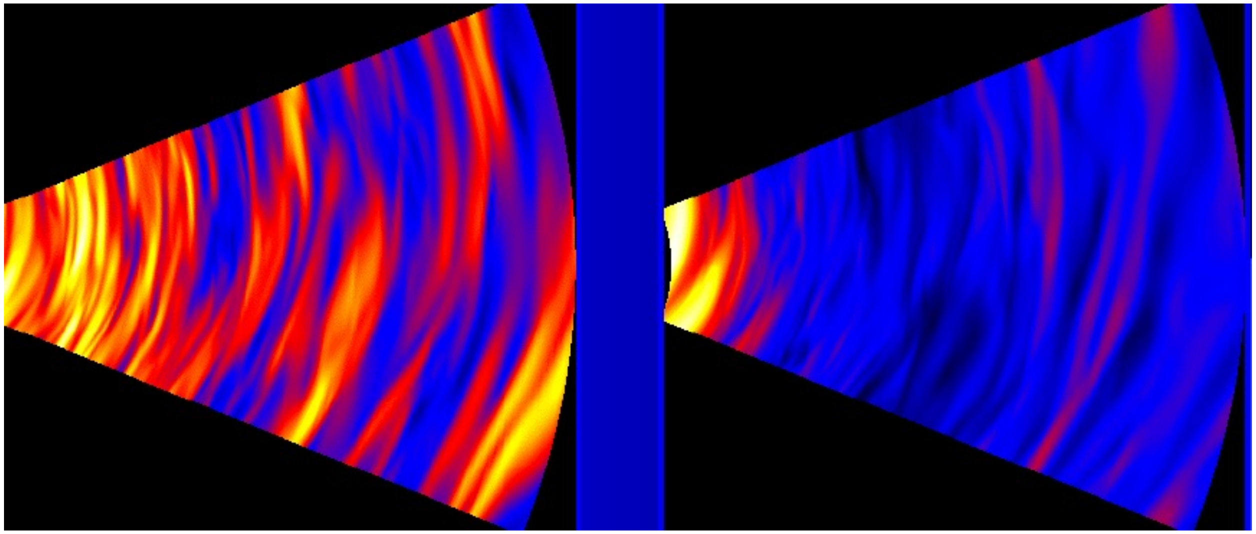
The fundamental problem is that one has to combine 3 very complex physical process

- Hydrodynamics
- Magnetic Fields
- Relativity

Why is it so hard to calculate?

- The physics of disks around BH is very messy in addition to the above complexities having a huge range of densities, temperatures and dynamical times.
- The interaction times of particles are dominated by gravity and electromagnetic forces rather than collisions which makes for large computational difficulties – complex codes and long run times

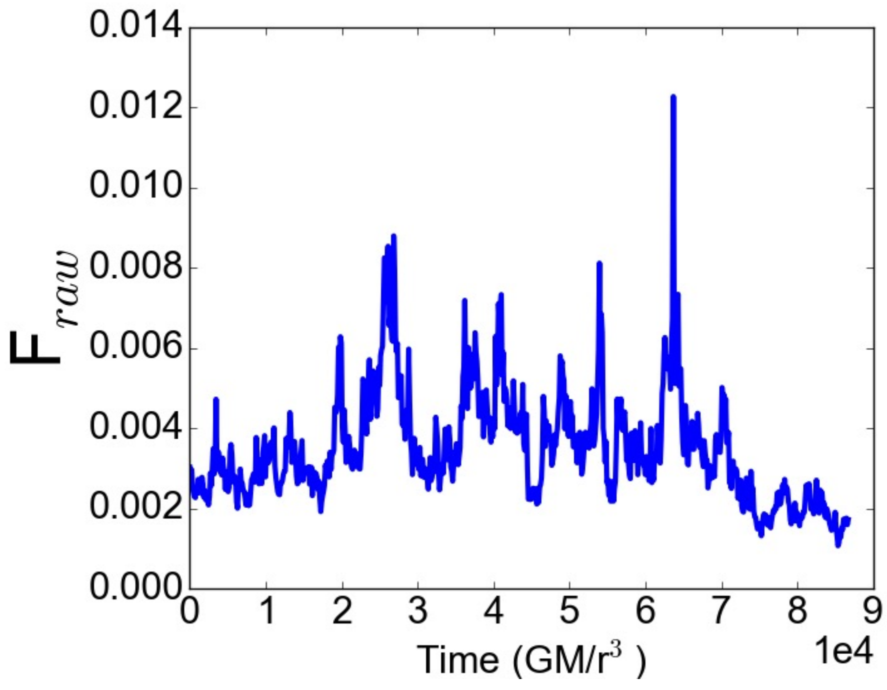
Image of Turbulence



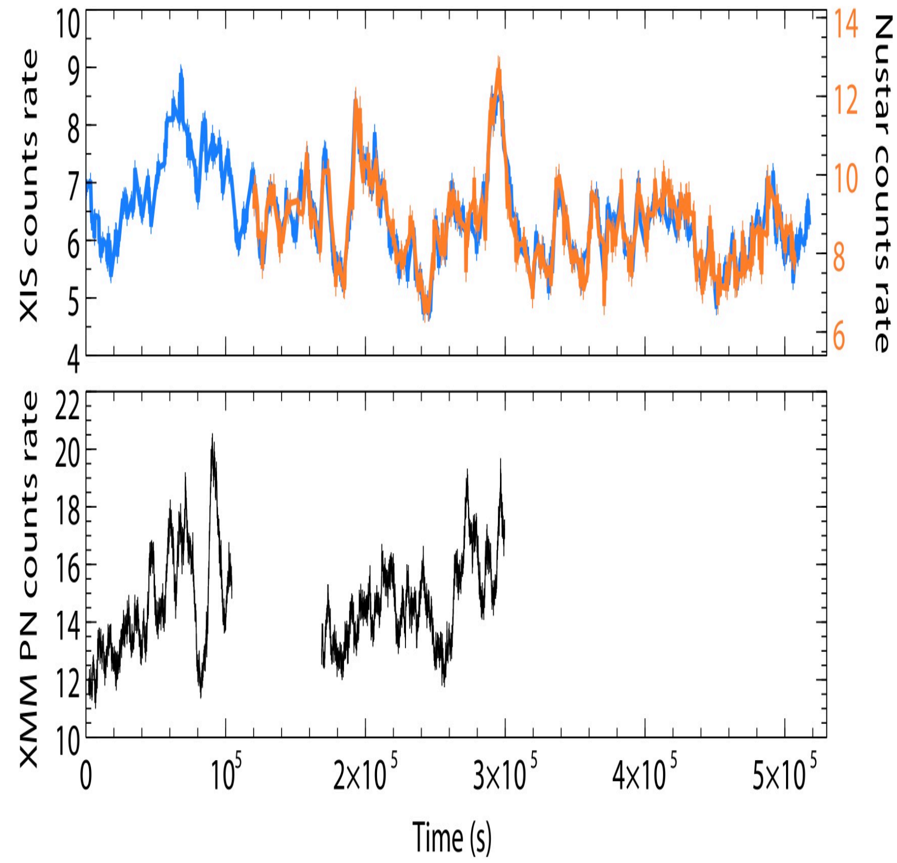
Brightness indicates how much energy is coming out-
2 snapshots out of a movie at different times

Simulation of Time Variability

Simulated accretion disk
(Hogg and Reynolds 2016)



X-ray data of accreting super-massive black hole in MCG-5-23-16 (Zoghbi et al. 2014)



"Other" Accretion Disks

There are many other places in nature where accretion disks occur

But the physical conditions are very different from near a black hole and so their emission and evolution are not the same

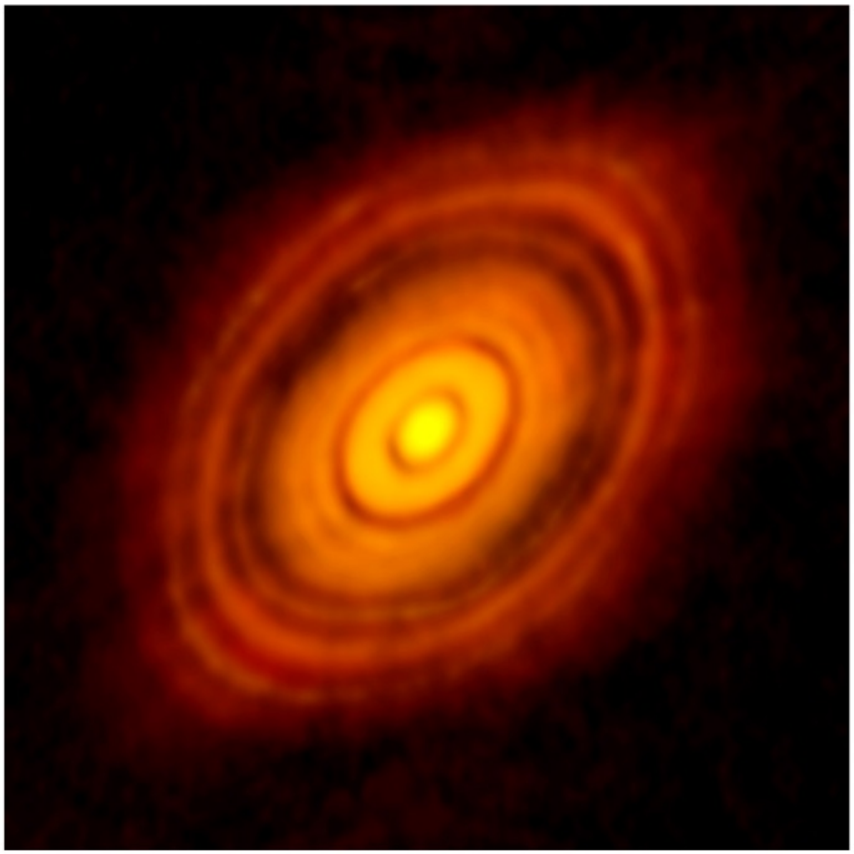
An Accretion Disk ?

Saturn's rings are so gas-poor that angular momentum transport is dominated by solid body collisions and disk-moon gravitational interaction- very different from our discussion so far

Saturn has much less gravity than a BH, so inner parts of the rings don't have to orbit much faster than the outer bits, thus friction is kept to a minimum and the disks are stable.

Proto-planetary Disks

"Generically" planets form in an accretion disk as the star is also forming- again very different physics than in BH systems
These are images of the gas in these disks



'igure 1.1 ALMA image of the young star HL Tau and its rotoplanetary disk in the mm continuum. Credit: ALMA/ESO

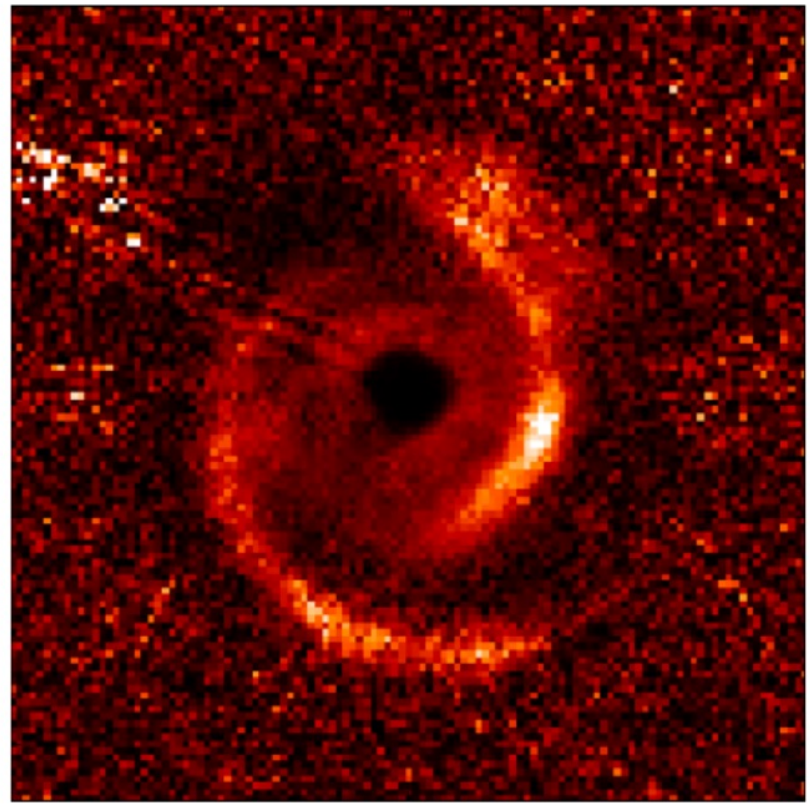


Figure 1.2 The protoplanetary disk MWC 758 as mapped in polarised scattered infrared with VLT/SPHERE. Credit: Benisty et al. (2015).